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Making Meyers Clear: An Exploration of the Chemistry and Art of Ceramic Glazes

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Sara Cat Williams

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Overview

A ceramic glaze is as a thin layer of glass that has fused with a clay body through the application of heat. A ceramic mug that is shiny because of the layer of glaze on its surface. Not all clay vessels are glazed. Terra Cotta pots are unglazed. Their porous structure is fantastic for not over watering plants, but terrible at holding coffee.

Glazes are both beautiful and practical. Practically, glazes can make fired clay stronger, more water resistant, or more easily cleaned. Artistically, glazes give brilliant colors and textures to otherwise monochrome clay. Glazes, however, are not colored by pigments. Mixing together a blue glaze and a yellow glaze may or may not result in a green glaze. This is because the colors, textures, and practical properties are a direct product of the chemical reactions between glaze components and clay.

Many artists buy their glazes from companies that offer a limited range of colors. This is convenient for those who need predictable, easy to use glazes and are not afraid to spend money. For some artists store bought glazes are not an option. Those making a large amount numbers of work might not have the financial means to buy small batches of glaze. Some artists might not be able to find the effects they want from store bought glazes, and still others might feel that they pose a risk to their originality as artists. If too many artists begin buying from the same companies, their work might begin to look the same. Whatever the reason, many artists continue to make their own glazes by hand, and it is these artists who keep glaze testing current and interesting.

Under some circumstances, glass can leach its materials into substances that it comes into contact with. One of the most common examples was leaded glass that was made popular in the 17th century. George Ravenscroft is credited with creating the technique of adding up to 30% lead oxide to glass in order to make it harder, easier to work with and easier to re-melt (Daly 2013). Unfortunately, we now know that concentrations of lead that high can leach into foods left in these containers.

Fig. 2. A 1670's glass decanter made with high concentrations of lead; now know to leech the toxic oxides after prolonged use.

Leaching is not a problem potter can ignore. Historically, lead and other leaching chemicals have been used extensively in glazes. Not all of the chemicals in glazes can leach, and not all of the chemicals in glazes which do leach are toxic. In order to be completely safe, there are some chemicals which just need to be avoided, including but not limited to lead, barium, and strontium.

Leaching is more likely to happen when a glaze has crazed or underfired. Crazing is a glaze flaw that causes hair-line cracks on a glazes surface. These cracks allow more contact between the materials inside the glaze and the substances coming in contact with the glaze (like you rmorning coffee).

Fig. 3. An example of Meyers crazing on a plate

Composition

At their core, glazes are made with the same materials as glass. However, the properties of glaze that allow it to hug complex clay forms without falling off or shattering make it unlike the glass in windows or on your car. Glazes gain these properties through the ratio of materials in its composition.

Ceramicists have grouped materials used in glazes by the function that they have in the glaze. They are the glass formers, the fluxes, and the refractory. Any one chemical can contribute to multiple categories. Furthermore, many materials that ceramicists call by one name are complex combinations of materials. For example, cobalt is used to give a deep translucent blue color, but it will also act as a flux. Some natural mined materials, such as Custar Fledspar, contribute to all three categories.

Many of us have heard that when lightning strikes the sands of a beach, sometimes a lump of glass is left in the crater. This is because some sands are comprised of quartz. Quart, or silicon dioxide, is made up of 1 silicon molecule covalently bound to 2 oxygen molecules. When heated, silicon dioxide lines up in 3 dimensional chains, which then interact to form a crystalline structure. Additional materials in the glaze affect the ways that these chains interact, either by stabilizing or breaking them.

Fig. 4. SiO_2 fired to ^5

The glass former is what does most of the work making the "body" of the glaze. The principal glass formula is silicon dioxide, SiO_2. Silica forms long chains of individual SiO_2 which then interlock to form a very strong 3 dimensional crystal network. Longer chains result in a stronger glass that will melt at a higher temperature. Unfortunately, the melting point of pure silica is 3,115 °F, far too hot a temperature for a traditional kiln firing. To lower the melting point of silica, fluxes are added.

Fig. 5. Ferro Frit 3214 fired to ^5.

The flux component of a glaze behaves like the gas pedal. It makes the glaze run. The flux lowers the overall melting point of the mixture by breaking of SiO_2 chains into shorter chains. These shorter chains require less heat energy to melt when compared to longer chains. This means that a glaze will melt faster in the kiln and have more time to be pulled down the pot by gravity. A glaze with a high ratio of flux is in danger of running off the pot and onto the kiln shelf below. For this reason, when performing glaze tests which involve the addition of fluxes, it is prudent to plan for potential running.

Fig. 6. Al_2O_3 fired to ^5.

If flux components are the green lights of a glaze, the refractory components are the yellow lights. Molecularly, the refractory elements tighten up the crystalline structure of the glaze by forming bonds with adjacent silica chains. Alumina oxide frequents glaze formulas most often as the primary stabilizer material. If too much refractory is added, the glaze is in danger of being brittle.

The three main functional glaze categories are related to the molecular formulas of glaze materials. A molecular formula of any chemical is a ratio of the molecules present in a given sample. Glass formers, so primarily silicon dioxide, tend to have a formula of RO_2, meaning that the ratio of oxygen molecules to other molecules is 2:1. Refractory materials often have a R2O3 with a ratio of oxygen to other molecules of 3:2. Fluxes often have the simple formula of RO, with a ratio of 1:1.

Fig.7. Bentonite hydrating in water.

In addition to the three main categories, ceramicists also use a category of materials known as modifiers. This catch all group includes any additives that don't fit neatly into the other three categories. Bentonite falls into this category. Bentonite is flocculent, which is a material that keeps particles in suspension for a longer period of time. By doing this, it is modifying the glaze, but not in a way that can be described by the other categories.

The ultimate goal of glaze formulation is to find a combination of these components that matches the kind of glaze that you are trying to achieve. Glazes fired to very high temperatures will require less flux than a glaze being fired to a lower temperature. In the case of glazes that attempt crystallization as a design element, stabilizing materials will inhibit crystal growth and should therefore be avoided. Whatever the case, returning to the three base glaze components can help make sense out of a glaze's behavior.

Formulation

The recipe that ceramicists use to make their magic is a glaze formula. In the same way that a recipe may be written several different ways, there are several ways that glaze formulas may be written that are used commonly.

The most commonly seen glaze formula is the 100% batch by weight representation. The main components are calculated to equal 100% with modifiers listed as additions to the 100%. No specific weight units are given in this formula because it is essentially a ratio of components.

Meyers Clear ^5	
3124	80
EPK	10
Flint	10
Bentonite	2

Fig. 8. 100% batch formula

The advantage of this is that you could make a batch of 100g or 1000kg easily, using the same formula. Ceramicists use this formula because it is easy to understand and work with.

When a different view is needed, ceramicists may turn to a unity formula, also known as a unity molecular formula or a Seger formula. This formula compares the ratio of oxide molecules, instead of the weight of the dry oxide materials. To change a percent formula to a unity formula, the weight of each material is divided by its molecular weight in order to obtain the number in moles of molecules. The materials are then grouped into the three function groups, body (acidic), refractory (amphoteric), and flux (basic). The amount of each type of oxide is then calculated using the percent formula and the total base oxides set equal to one. Software that helps with these calculations are available and quite useful. Nerveless, it is best to be able to do the conversion yourself. I have changed Meyers clear from its 100 Batch formula into a unity formula as an example.

Step 1. Determine all of the chemicals present in each glaze material. This information may be found online. All of the materials mentioned have a full breakdown in the materials section of this paper.

Step 2. Add the chemicals' weights together and then divide all of them by the total number. This should result in the total percent of each oxide in the glaze.

SiO_2 59.71%

TiO_2 0.03 %

Al_2O_3 11.84%

MgO 0.01%

P_2O_5 0.01%

Fe_2O_3 0.07%

Na_2O 5.12%

CaO 11.46%

K_2O 0.61%

B_2O_3 11.12%

Step 3. Divide the materials in to the three base categories, body, refractory, and flux.

Body (RO2)		Refractory (R2O3)		Fluxes (RO)	
SiO_2	59.17%	Al_2O_3	11.84%	MgO	0.01%
TiO_2	0.03%			P_2O_5	0.01%
				Fe_2O_3	0.07%
				Na_2O	5.12%
				CaO	11.46%
				K_2O	0.61%
				B_2O_3	11.12%

Step 4. Divide each material by its molecular weight in order to determine the number of molecules present in each material.

SiO_2	59.71 / 60.0g per mole	= 0.995
TiO_2	0.03 / 79.9g per mole	= 0.0004
Al_2O_3	11.84 / 102.0g per mole	= 0.116
MgO	0.01 / 40.3g per mole	= 0.0002
P_2O_5	0.01 / 141.9g per mole	= 0.000
Fe_2O_3	0.07 / 160.0g per mole	= 0.0004
Na_2O	5.12 / 62.0g per mole	= 0.083
CaO	11.46 / 56.1g per mole	= 0.204
K_2O	0.61 / 94.2g per mole	= 0.006
B_2O_3	11.12 / 69.600g per mole	=0.160

Step 5. Plug the calculated molecular amounts into the unity formula format. This shows the molecular ratios of the glaze.

Glass formers (RO2)		Refractory (R2O3)		Fluxes (RO)	
SiO_2	0.995	Al_2O_3	0.116	MgO	0.0002
TiO_2	0.0004			P_2O_5	0.000
				Fe_2O_3	0.0004
				Na_2O	0.083
				CaO	0.204
				K_2O	0.006
				B_2O_3	0.160

Step 6. Add together the fluxes in the RO column.

0.0002 + 0.000 + 0.0004 + 0.083 + 0.204 + 0.006 + 0.160 = 0.4536

Step 7. Divide the molecular weight of each all the materials, flux, refractory, and glass formers, by the number calculated in step 6. If the math is correct, the total number of flux should equal 1.

SiO_2 0.995/ 0.4536 = 2.193

TiO_2 0.0004/ 0.4536 = 0.0009

Al_2O_3 0.116/ 0.4536 = 0.256

MgO 0.0002/ 0.4536 = 0.0004

P_2O_5 0.000 / 0.4536 = 0.000

Fe_2O_3 0.0004 / 0.4536 = 0.0009

Na_2O 0.083 / 0.4536 = 0.183

CaO 0.204 / 0.4536 = 0.450

K_2O 0.006 / 0.4536 = 0.013

B_2O_3 0.160 / 0.4536 = 0.353

Glass formers (RO2)		Refractory (R2O3)		Fluxes (RO)	
SiO_2	2.193	Al_2O_3	0.256	MgO	0.0004
TiO_2	0.0009			P_2O_5	0.000
				Fe_2O_3	0.0009
				Na_2O	0.183
				CaO	0.450
				K_2O	0.013
				B_2O_3	0.353

Fluxes: 0.0004 + 0.000 + 0.0009 + 0.183 + 0.450 + 0.013 + 0.353 = 1.000

Glaze Materials

Glaze makers must understand the materials that they use. What follows is a brief explanation of all of the glaze materials that I personally used during my testing of Meyers Clear.

Many glaze materials are a combination of oxides. In these cases, potters often list both the percentage of oxides in the material under the analysis column, and the formula weights of the oxides under the formula column. LOI refers to materials that are Lost On Ignition, i.e., burn away.

Barium Carbonate

Alternate names: $BaCO_3$, Witherite

Oxide	Analysis	Formula
BaO	77.66%	1.000
CO_2	22.34	
Oxide Weight		153.30
Formula Weight		197.40

Barium carbonate most often used in glazes for its mattifying and crystallization properties. It does not change the coloration of glazes.

Bentonite

Alternate names: Montmorillonite

Oxide	Analysis	Formula
CaO	1.00%	0.141
MgO	2.00%	0.392
K_2O	1.00%	0.084
Na_2O	3.00%	0.383
Al_2O_3	20.00%	1.551
SiO_2	59.00%	7.763
Fe_2O_3	3.50%	0.173
LOI	10.00	
Oxide Weight		707.76
Formula Weight		786.40

Bentonite is a material commonly added to both clay and glazes. Among other things, it acts as a flocculent, keeping glaze particles in suspension for longer. Because it can absorb a large volume of water, it is often hydrated separately from the other glaze materials for a longer period of time.

Chrome Oxide

Alternate names: Cr_2O_3, Chromium (III) Oxide

Oxide	Analysis	Formula
Cr_2O_3	131.58%	1.000
Oxide Weight		152.00
Formula Weight		152.00

Chrome Oxide is a refractory colorant that produces bright green glazes.

Cobalt Oxide

Alternate names: CoO, Cobalt (II) Oxide

Oxide	Analysis	Formula
CoO	93.35%	1.000
O	6.65	
Oxide Weight		74.92
Formula Weight		80.26

Cobalt Oxide makes a strong, deep blue even in glazes even at very low concentrations

Copper Carbonate

Alternate Names: $CuCO_3$

Oxide	Analysis	Formula
CuO	64.40%	1.000
CO_2	35.62	
Oxide Weight	79.54	
Formula Weight		123.55

Copper Carbonate is a volatile flux that will remain green – blue in oxidation firings.

Copper oxide

Alternate names: CuO,

Oxide	Analysis	Formula
CuO	100.00%	1.000
Oxide Weight		79.54
Formula Weight		79.54

One of the oldest glaze colorants, Copper oxide will remain green- blue in oxidation firings, and reduce to Cu_2O and a red color in reduction firings.

EPK

Alternate Names: Edgar Plastic Kaolin

Oxide	Analysis	Formula
CaO	0.18%	0.009
MgO	0.10%	0.007
K2O	0.33%	0.010
Na_2O	0.06%	0.003
P_2O_5	0.24%	0.005
TiO_2	0.37%	0.013
Al_2O_3	37.36%	1.000
SiO_2	45.73%	2.077
Fe_2O_3	0.79%	0.013
H_2O	1.40	
LOI	13.20	
Oxide Weight		232.50
Formula Weight		272.92

EPK contains high levels of both glass formers and refractory elements

Ferro Frit 3124

Alternative names: Leadless high calcium borosilicate frit

Oxide	Analysis	Formula
CaO	14.28%	0.711
K_2O	0.68%	0.020
Na_2O	6.40%	0.289
Al_2O_3	10.01%	0.274
B_2O_3	13.74%	0.552
SiO_2	54.94%	2.555
Oxide Weight		279.65
Formula Weight		279.65

This is already very glaze-like because it contains all three of the major functional groups.

Flint

Alternative names: SiO_2, Silica.

Oxide	Analysis	Formula
CaO	3.00%	1.000
MgO	0.10%	0.046
SiO_2	94.00%	29.248
Fe_2O_3	0.10%	0.012
H_2O	3.00	
Oxide Weight		1817.64
Formula Weight		1873.86

Silica is the primary glass former of all glazes.

Manganese Carbonate

Alternative names: MnCO3

Oxide	Analysis	Formula
MnO	61.62%	1.000
CO_2	38.38	
Oxide Weight		70.90
Formula Weight		115.06

Manganese will turn brown in glazes that contain alumina, and violet in glazes which do not.

Rutile

Alternative names: Iron Titanium Mineral

Oxide	Analysis	Formula
TiO_2	90.00%	1.000
Fe_2O_3	10.00%	0.055
LOI	0.10	
Oxide Weight		88.78
Formula Weight		88.87

Rutile is a name given to the natural crystals of titanium dioxide. It produces many of the interesting surface effects that potters desire.

Kilns and Firing

When it comes down to it, potters must fire glazes in a kiln and that is perhaps the biggest difference between glazing and other forms of coloration. Historically, wood and coal fire kilns were the only options available to potters. In Korea during the 12th century, potters, sometimes ones in direct competition with one another, would form groups to constantly tend to large wood fire kilns for however many days it took to fire their work. Nowadays, potters also have the option of firing their work in electric kilns. Regardless of the power source, however, kilns all accomplish the same job. That job is to evenly heat ceramic ware to high temperatures.

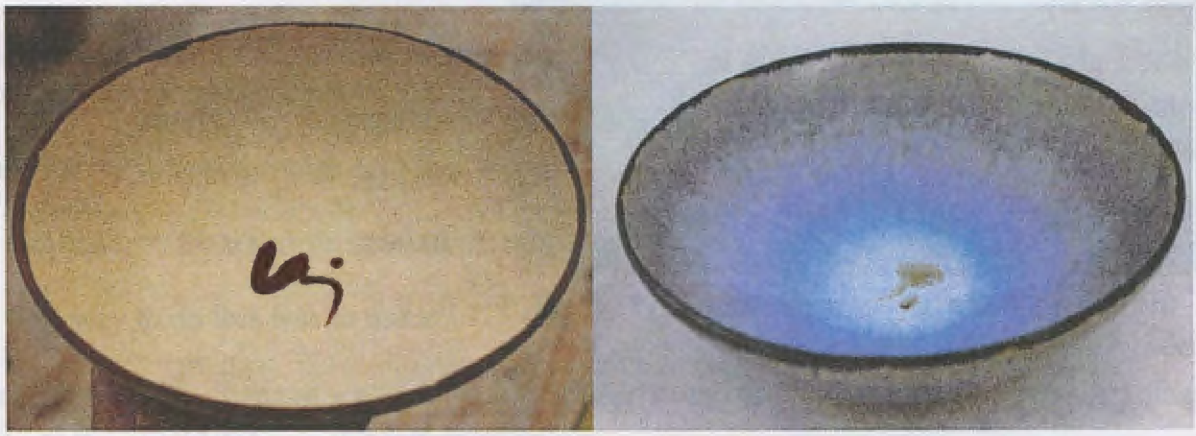


Fig.9. A cobalt glazed bowl with iron oxide details before and after it has been fired.

When potters delineate the difference between baking in an oven and firing in a kiln, they are doing so because there are both semantic and practical differences. Semantically, the phase "firing in a kiln" communicates that pottery of some kind is being discussed. Practically, a kiln can reach much higher temperatures and is made with specific materials.

There are two main variables to consider when firing ceramic work, temperature and atmosphere.

In glaze literature, you would be hard pressed to find instructions written as "fire the piece to 2,246°F by increasing the heat by 150°F every hour for 15 hours or by 200°F for 11 hours." Instead, you would see "fire to ^7." These two instructions, however, mean the same thing. The symbol "^" represents a cone. A cone, in turn, is a term used to represent both the temperature and time that a piece should be fired to. It is essentially a measure of the amount of work done by heat.

Fig.10. Pyrometric cones that have been fired to ^10

Originally, cones were physical objects. Before the invention of digital thermometers, potters had to have a way of consistently firing their pieces to the same temperature for a similar amount of time. One way to do this was to use a material that visibly changed when the wanted temperature was reached, like a cone shape that would slump at a certain temperature. These became known as pyrometric cones (*pyro* as in fire and *metric* as in measure, meaning a measure of fire) and are still in use today. However, electric kilns can now be programed very exactly and therefore the need for physical cones is not as pressing. However, the nomenclature lives on.

A snag commonly hit by beginning students is the numbering system used for cones. The cone which corresponds to the least amount of heat absorbed by materials is ^022 at 1094°F. As the temperature increases, the numbers decrease until ^01 is reached at around 2080°F. Once ^01 is reached, the number system begins to count up starting from ^1 all the way to ^15 at 2615°F.

kiln is starved of oxygen, making the glaze more likely to pull oxygen molecules from elsewhere. A reduced atmosphere can be accomplished in two ways. If oxygen is not allowed to enter the environment of the kiln for a long enough period of time, the kiln may starve itself of oxygen. If this is not fast enough, other elements such as fire may be introduced to use some of the oxygen in the kiln and reduce the overall atmosphere.

The availability of oxygen has dramatic implications for color development because glazes are most commonly colored with materials that contain some amount of oxygen bound to another molecule. These materials are known as oxides. Many oxides are capable of binding different amounts of oxygen which results in a different overall ratio of oxygen molecules to other bound molecules. These are known as oxidation states. When an oxide is "reduced" to a lower oxidation state, it is because the amount of oxygen has been reduced compared to the number of other molecules. It so happens that different oxidation states of oxides are often different colors as well. For example, copper oxide contains one copper molecule for every molecule of oxygen, which gives it the formula of CuO. This oxidation state of copper is a bright green- blue. When cooper oxide is reduced to a state with an unequal ratio of two molecules of copper to one molecule of oxygen, Cu_2O, it becomes a deep red. So when CuO is added to a glaze and then fired in an atmosphere with plenty of oxygen, it remains in the same oxidation state and the resulting glaze will be a blue-green. If that same glaze is fired in an atmosphere which is starved of atmosphere, it will change oxidation states and result in a deep red glaze.

Fig.12. Meyers Clear with 3% added copper fired in oxidized, left tile, and reduced, right tile, atmospheres

Glaze Flaws

To quote a wise teacher of mine, “Glazes are like cheese, they melt and they stick.” When melted successfully, cheese becomes creamy fondue bliss. When melted unsuccessfully, cheese can become a hard hockey puck of milk solids and a greasy layer of oil. The success of glazes is also dependent on the conditions that affect its melting. When these conditions are not correct, glaze flaws may form. Some glaze flaws are made intentionally for artistic effect, but many are not ideal for food-safe glazes.

Glazes do not change from powder to glass instantly in a kiln. There are two important chemical reactions that must occur for a glaze to fully mature, and those reactions take time. The first is the formation of the crystalline structure of the clay body which happens between temperatures 200° and 400° and is called *cristobalite development*. The second reaction occurs at the melting point of silica, 570°, and is called *quart inversion* as it is the time that silca (quartz) changes form. If a kiln spends too much or too little time at either of these critical periods, the result may be negative.

Cristobalite development is closely related to a phenomena known as glaze fit. The fit of a glaze is defined as how similarly a glaze expands and contracts compared to its clay body. All ceramic materials expand when they are heated and contract when they are cooled. Some of this contraction occurs because of water loss, but some occurs because of the development of the crystalline structure. A crystalline structure can fit more molecule into less space because it packs the molecules in a more organized manner much in the same way that more clothes will fit into a suitcase if they are folded first. As many married couples already know, partners who try to share the same space will have conflict if one individual uses more space than they agreed upon.

Crazing

Fig.13. Two examples of Crazing in Myers Clear

Crazing is the appearance of fine cracks on the surface of a glaze. Closely related to the fit of the clay body, crazing occurs because the glaze contracts more than its clay body. This differential puts stress on the glaze which is relieved by the cracking. It is an effect which falls into the intentional category as often as it does the unintentional category. In functional ware, however, crazing is often unintentional because the cracks can be a breeding ground for bacteria.

Meyers Clear is a particularly egregious offender in the area of crazing. Because the problem comes from a difference in heat expansion between the clay and glaze, methods to correct crazing focus on matching these two variables. The addition of silica in small increments is suggested as well as making sure that the kiln warms and cools slowly.

Pinholeing and Pitting

Fig.14. Example of pitting, left image, and pinholeing, right

Pinholes are small holes on the surface of glaze that appear on finished ware. Pitting is a similar phenomenon but the holes are not deep enough to reach the clay body. Like crazing, both flaws increase the porosity of glazes by allowing more contact between the clay body and its environment. This makes it a flaw to avoid when making glazes intended to be food safe. Much pinholeing can be avoided by rubbing a glaze before it is fired to close any pockmarks that might have formed when the glaze was applied. Sometimes, though, pinholeing and pitting happen because a glaze is not fired to maturity and the gases which normally would have had time to vent become trapped under the surface of the glaze.

Blistering

Fig.15. A glaze that blistered

Blistering occurs when large bubbles form on the surface of a glaze. When these bubbles pop open, the shards and edges made are razor sharp. For this reason, this glaze flaw can instantly make a piece not food safe, as the risk of ingesting a shard or cutting your mouth on an edge is too dangerous to risk.

This flaw can be the result of glaze being applied too thickly or imperfections not being rubbed out of a glaze before firing. Often, very fluid glazes applied to the inside of cups will run into the corners, increasing the thickness and increasing the chance of bubbling. Overfiring can also cause blisters by making the glaze boil which can result in air bubbles becoming trapped as the glaze cools again.

How to make a glaze.

If you can bake a batch of muffins, you

Fig.17. Bentonite hydrating.

can make a glaze. This is a short explanation of how to make a glaze intended for testing. Before you begin, you have to gather some supplies. Besides what might be expected, safety

Fig.16. Glaze making materials

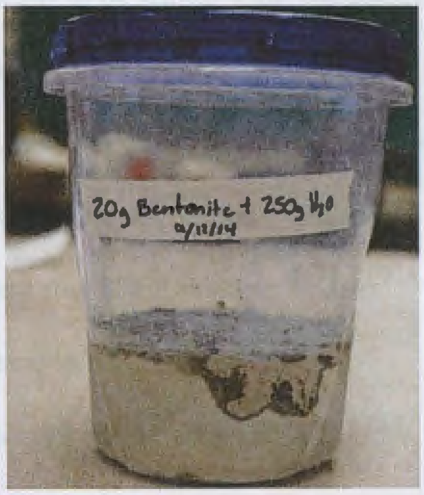


Fig.17. Bentonite hydrating

gear is also needed. Chemicals should not be inhaled, handled, or let into eyes. Ideally glazes should be made in a well-ventilated area with long pants and sleeves, goggles, and a particle mask. If you are using materials which need extra time to hydrate, such as bentonite that needs to be done before the main materials are weighed out, and always add powders to liquids. Next, the base materials need to be weighed out and mixed together dry before being added to distilled water, similar to the muffin method of adding dry to wet ingredients.

Fig.18. Weighing out materials

Once the base glaze is together, it may be equally aliquoted to pre-labeled containers. Additives wanting to be tested should be added at this time. At this point, the glaze needs to hydrate for a little while, between a day and three days. Once hydrated, the glaze needs to be stirred well. An eclectic hand mixer is often good for this. Lastly, the glaze needs to be sieved to remove any lumps of material and stirred a final time. Glazes need to be kept in an airtight container that is clearly labeled.

Fig.19. Oxides after being added to base glazes

Fig.20. Labeling is everything

Glaze Testing

Test Tiles

Test tiles may be thrown on a wheel or hand-built. Wheel made tiles are made by making a large ring, allowing it to dry slightly, and cutting the ring into small sections. These tiles work well and are very quick to make.

Hand-built tiles are made either by cutting individual tiles out of a flat sheet of clay or by extruding them. These tiles take a bit more time, but have one key advantage over wheel thrown tiles, the ability to be fired upright and then displayed flat. This is done by making a score line in the bend of the clay (fig.22) so the back piece may be gently knocked off with a hammer after firing. Holes are placed so that they can hang around bucket lids or on walls.

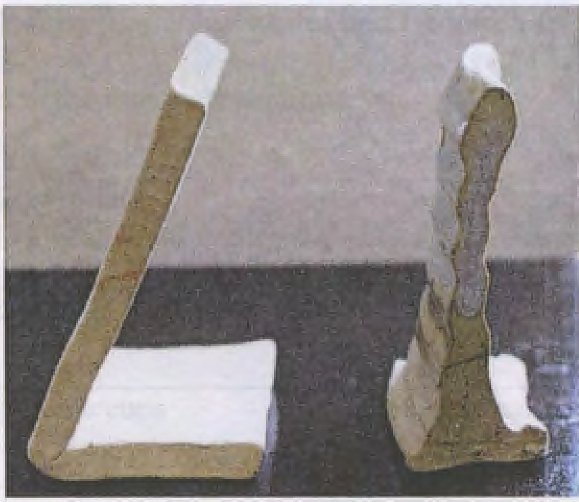


Fig.21. The difference between hand-built tiles (left) and wheel thrown tiles (right)

Fig.22. The clay is scored along the fold before firing

Color Blend

Introduction

A color blend is the simplest glaze test to understand and the best to begin with. It is also a great way to get to know your glaze. Essentially, a color blend involves making a large batch of the base glaze you would like to test and adding in things which will change its appearance and behavior in a systematic way.

The way to decide what materials to test is simple; determine what glazes you are interested in developing and research what those glazes are made of. For this test, I wanted to look at oxides which would change the color of the glaze without changing the texture and melting temperature. I was also interested in opaque glazes. This test included 9 additional materials for a final 9 test glazes and 1 control. Information on all the additional materials are all included in the materials section.

Materials

10 bisque fired tiles	Glaze materials	Sieve
10 disposable cups	Spoon or spatula	Scale
Distilled water	Sharpie	Particle Filter Mask
Gloves	Eye Protecting googles	

Method

3124	80g		800g
EPK	10g	X 10tests	100g
Flint	10g		100g
Bentonite	2g		20g

First, the amount of base glaze needed for 10 glaze tests of 100g each was calculated. Next, 20g of bentonite was hydrated in 500ml of distilled water in a transparent plastic container for 3 days. The remaining base glaze components (Frit3124, EPK, and flint) were weighed out on a triple beam balance scale and thoroughly mixed before adding water and bentonite mixture. This mixture was then left to hydrate, undisturbed, for 2 more days. Once the mixture was hydrated, it was thoroughly stirred using an electric hand mixer and divided equally between the 10 labeled test cups so that every cup contained approximately 100g of base glaze.

The additional components were weighed out and added to their respective cups, as shown in fig.23. Before applying the glaze tests to their corresponding labeled clay tiles, each test was mixed for a final time. It was noted at this time that the glaze consistency was on the thick side, however, more water was not added. Each test tile was then dipped into its respective glaze test 3 times for 3 seconds each time, allowing each layer to dry completely before dipping again. The tiles were then left to dry over-night. Lastly, pinholes were rubbed out and the tiles were fired to ^5.

Test	Additive	Amount
1	Fe_2O_3 (Iron Oxide)	3g
2	Titanium	2g
3	Lithium Carbonate	3g
4	Chromium Oxide	0.5g
5	Copper Carbonate	2g
6	Rutile	5g
7	Barium Carbonate	0.5g
8	Manganese Carbonate	2g
9	Cobalt Oxide	1g
10	Dolomite	11g

Fig.23. Oxides added to each glazes test

Results and Discussion

The first thing noticeable in this test is that the glaze is very thick. This is seen on especially tests 8, 9, and 10 by the large edge of the bottom of the glaze. This is partially due to the thickness of the glaze when it was applied, but it is also known that oxides added to glazes lower the melting point which increases the amount that the glaze will run. Based on this, it can be inferred that cobalt, zircopax, barium and iron most likely will increase the run on this base glaze.

Fig.24. All test tiles in order from left top to bottom right

Test 1a	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Fe_2O_3	3

Test 2a	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
TiO_2	2

Test 3a	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
$LiCO_3$	3

Test 4a	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
$CuCO_3$	0.5

Test 5a	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Cr_2O_3	0.5

Test 6a	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Rutile	5

Mixed color blend

Introduction

The term "mixed color blend" is not a technical term, but I have chosen to use it because it seems to be the best description of this test. When I finished the previous color blend, I was interested in what some of the materials used for separate glaze tests would look like mixed together. In particular, I was interested in the possibility of crystalline glazes. Crystallization in glazes can be considered a flaw, but many in the artistic community, myself included, find it beautiful. *Sacco Copper Black Blue Green with White Crystals* in The Ceramic Glaze Handbook, (Burleson 2003) is a playful crystalline glaze that gets most of its qualities from high concentrations of cooper carbonate and manganese dioxide. In order to quickly see if Meyers had the potential to make similar crystallization, I combined the two glazes that I had made previously which contained copper carbonate and manganese dioxide. It was an interesting idea, so I combined the remaining eight glazes and therefore created a "mixed color blend."

Materials

6 bisque fired tiles	Particle Filter Mask	Sieve
Previously made glazes	Spoon or spatula	Scale
Distilled water	Sharpie	
Gloves	Eye Protecting googles	

Method

First, the expected final amounts of oxides were calculated using the formula $C_1V_1 = C_2V_2$, where C refers to the concentration of the added material in grams and V equals the total volume of the glaze solution in grams. This is necessary for tests that mix more than 2 glaze tests together as the final amounts are not easily intuited. Calculations for test 1b and 5b are shown as examples.

Test 1b: 3g Li_2O_3 × 100g Glaze = Xg Li_2O_3 × 200g Glaze

300 = Xg Li_2O_3 × 200g Glaze

X = 1.5 g Li_2O_3

Test 5b: 1.5g Li_2O_3 × 200g Glaze = Xg Li_2O_3 × 300g Glaze

300 = Xg Li_2O_3× 300g Glaze

X = 1g Li_2O_3

Next, glaze tests from the previous color blend were mixed together. The glaze was then applied to the test tiles using the dip method. The tiles were allowed to dry over-night before having the pinholes rubbed out. The tiles were fired to ^5.

Results and Discussion

I consider this test a success, even if no crystallization was seen. Like many freshmen in their first general chemistry lab, I learned that concentration is everything. More material is needed to ensure crystallization.

The colors are diluted because the concentrations of oxides in the glazes was significantly lowered as compared to the first color blend. However, these pale colors are really quite lovely and can undoubtedly be used as functional glazes. Additionally, these glaze tests were applied more thinly and less pinholeing was seen as a result.

Fig.25 Glazes resulting from the mixed color blend in order

Test 1b	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
$LiCO_3$	1.5
Cr_2O_3	0.25

Test 2b	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
$MnCO_3$	1
Rutile	3.5

Test 3b	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Fe_2O_3	1.5
$CuCO_3$	1

Test 4b	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.5
Dolomite	5.5

Test 5b	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
$LiCO_3$	1
Cr_2O_3	0.33
TiO_3	1.33

Test 6b	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
$MnCO_3$	0.6
Rutile	1.6
$BaCO_3$	0.2

Line Blend

Introduction

Just like the simple color blend, the line blend holds some variables constant while changing other in a defined way. If I was doing this same test with bacterial colonies, I might call it a dilution assay. Many line blends are done with additions to glazes, such as an oxide or colorant. Several tests of that nature are shown in the additional tests section. In this line blend, however, I was interested in the base formula itself. I hypothesized that adding more silica and decreasing the amount of EPK might decrease the amount of crazing. With that in mind, I designed the test so that all three of the primary components were varied in specific ranges separately from each other.

A different clay body was used for the test tiles in this test in order to try and achieve more consistent results. The clay was called Zellastone, is a ^5 - ^6 stoneware, and can be commercially bought through *Highwater Clays*. The clay used in previous and tests is mixed in the school's studio and can be different from one batch to another. It is a combination of reclaimed clay mixed with Red art clay, Nef Sye, and SiO_2 sand. Because it is not sent through a pug mill, this class clay is looser and less plastic.

Materials

30 bisque fired tiles	Glaze materials	Sieve
30 disposable cups	Large Tablespoon	Scale
Water	Sharpie	

Method

	1	2	3	4	5	6	7
3124	65g	70g	75g	<u>80g</u>	85g	90g	95g
Flint	9.25	9.5	9.75	<u>10</u>	10.25	10.5	10.75
EPK	9.25	9.5	9.75	<u>10</u>	10.25	10.5	10.75

Fig.26. The range of materials with tiles containing the original glaze composition indicted by underline.

First, the range of the materials was calculated so that the middle of each line blend would equal the ratio of materials of the original glaze as shown in fig. 26. Due to the nature of this test, bentonite for the entire batch could not be hydrated at the same time. 10 grams H_2O was added to each 21 test cup followed by 2g of bentonite. This was left to hydrate for 2 days. The remaining base glaze components (frit 3124, EPK, and flint) were weighed out on a triple beam balance scale and added to the water and bentonite mixture (fig.26). The two additional components of each was added in their normal amounts if not otherwise specified. This mixture was then left to hydrate, undisturbed, for an additional day.

Once the mixture was hydrated, it was thoroughly stirred using an electric hand mixer before being applied to their correspondingly labeled clay tiles. Each test tile was then dipped into its respective glaze 3 times for 3 seconds each time, allowing each layer to dry completely before dipping again. The tiles were then left to dry over-night. Lastly, pinholes were rubbed out and the tiles were fired to ^5.

Results and Discussion

One of the largest takeaways from this test is the assurance that this is a very finely tooled glaze. Even at the extreme ends of my ranges, the glazes did not consistently show differences from the original. Therefore, it seems that in order to see dramatic differences, the components need to be altered more.

When first removed from the kiln, only two of the tiles, 20cC and 21cC, showed crazing. Over the next three days as the tiles fully finished cooling, all but three of the tiles crazed. There does seem to be some indication that a high proportion of silica may reduce the time it takes for crazing to occur. This result was enough to encourage me to do an additional triaxial blend using these ratios.

Fig.27. Glazes resulting from the line blend in their numerical order.

Test 1cA	^5 Oxidation
3124	65
EPK	10
Flint	10
Bentonite	2

Test 2cA	^5 Oxidation
3124	70
EPK	10
Flint	10
Bentonite	2

Test 3cA	^5 Oxidation
3124	75
EPK	10
Flint	10
Bentonite	2

Test 4cA	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2

Test 5cA	^5 Oxidation
3124	85
EPK	10
Flint	10
Bentonite	2

Test 6cA	^5 Oxidation
3124	90
EPK	10
Flint	10
Bentonite	2

Test 7cA	^5 Oxidation
3124	95
EPK	10
Flint	10
Bentonite	2

Test 8cB	^5 Oxidation
3124	80
EPK	10
Flint	9.25
Bentonite	2

Test 9cB	^5 Oxidation
3124	80
EPK	10
Flint	9.5
Bentonite	2

Test 10cB	^5 Oxidation
3124	80
EPK	10
Flint	9.75
Bentonite	2

Test 11cB	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2

Test 12cB	^5 Oxidation
3124	80
EPK	10
Flint	10.25
Bentonite	2

Test 13cB	^5 Oxidation
3124	80
EPK	10
Flint	10.5
Bentonite	2

Test 14cB	^5 Oxidation
3124	80
EPK	10
Flint	10.75
Bentonite	2

Test 15cC	^5 Oxidation
3124	80
EPK	9.25
Flint	10
Bentonite	2

Test 16cC	^5 Oxidation
3124	80
EPK	9.5
Flint	10
Bentonite	2

Test 17cC	^5 Oxidation
3124	80
EPK	9.75
Flint	10
Bentonite	2

Test 18cC	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2

Test 19cC	^5 Oxidation
3124	80
EPK	10.25
Flint	10
Bentonite	2

Test 20cC	^5 Oxidation
3124	80
EPK	10.5
Flint	10
Bentonite	2

Test 21cC	^5 Oxidation
3124	80
EPK	10.75
Flint	10
Bentonite	2

Triaxial Blend

Introduction

A triaxial blend looks intimidating at first glance. The trick lies in thinking of it as a collection of individual line blends in which any line you draw through the triangle equals 1 line blend. This is understood more easily by looking at a diagram such as fig.28. The benefit that a triaxial blend offers is the ability to produce many subtle variations of three variables. Tests like this are most helpful when you are already familiar with the glaze you are working with and want to look closely at a few additions. For this test, I choose rutile, cobalt, and Zircopax as my variables.

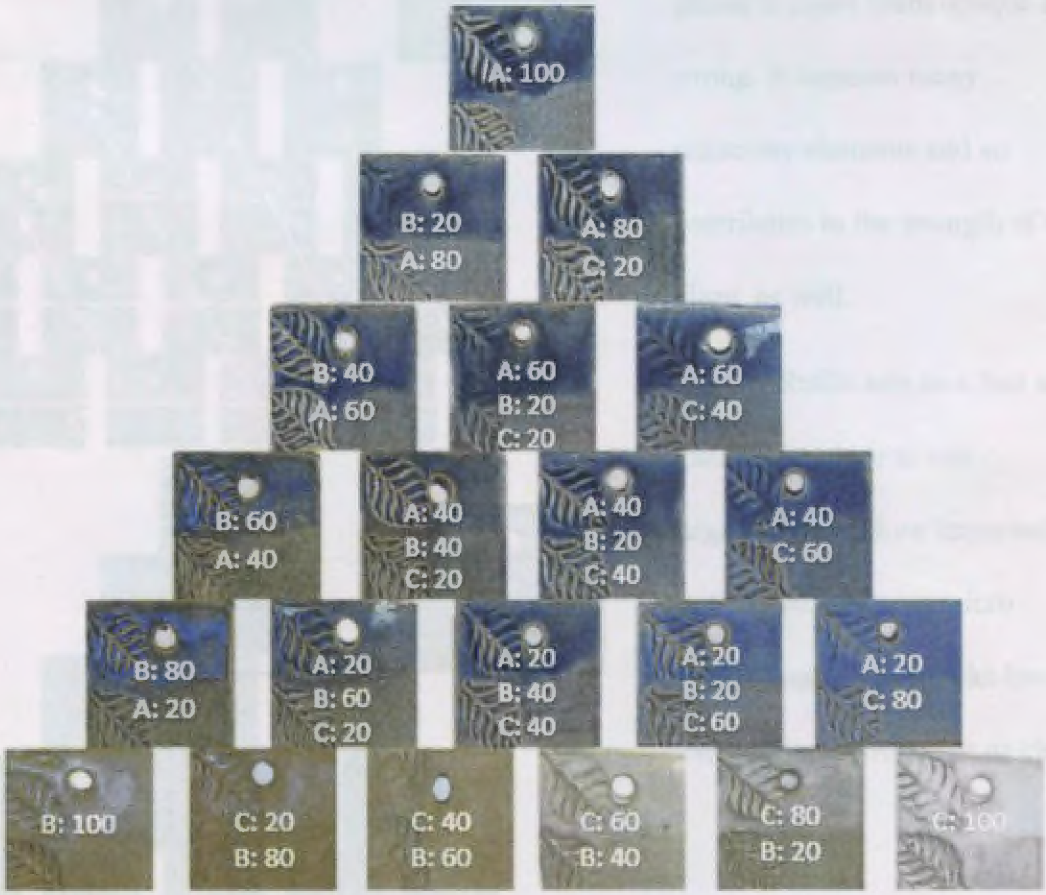
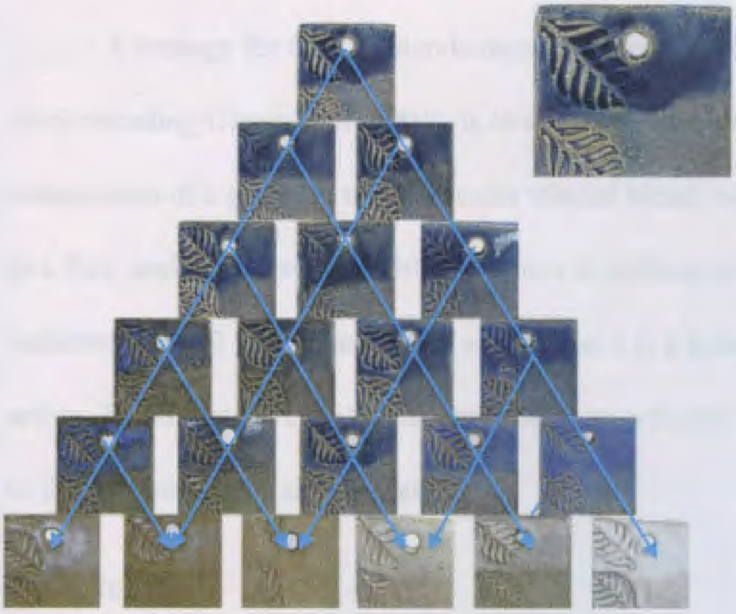
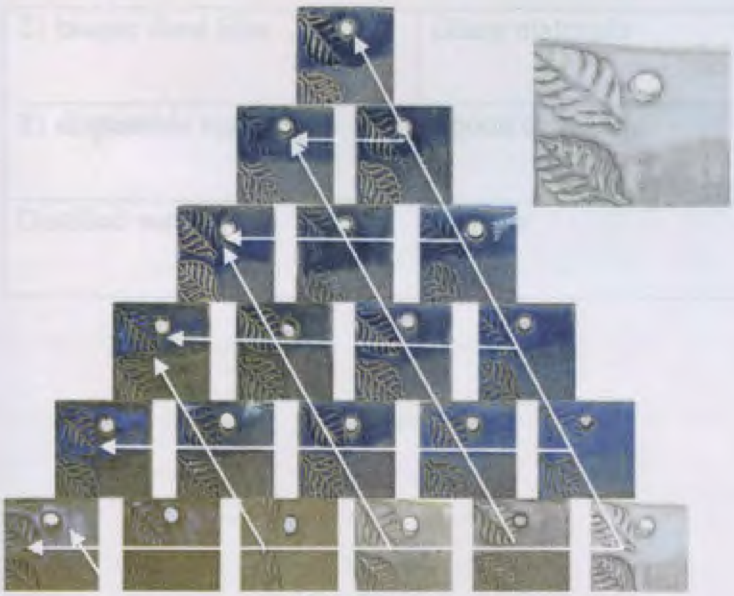


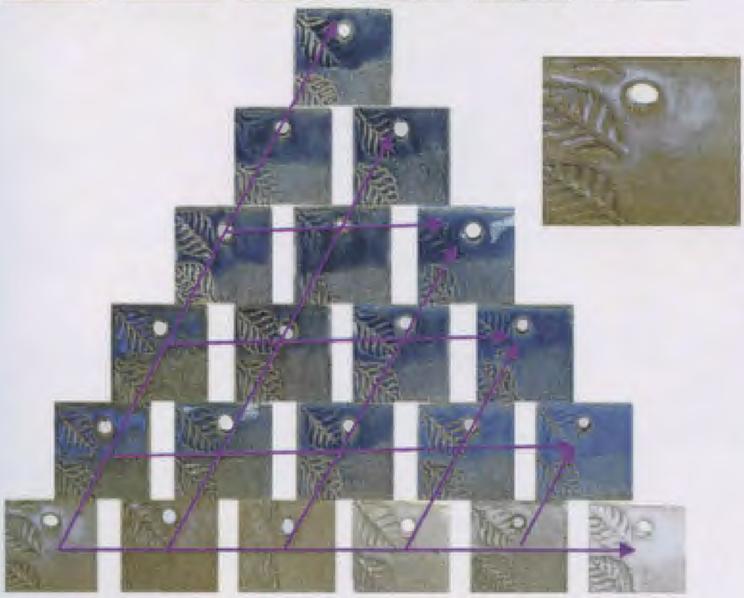
Fig.28 The General outline of a triaxial blend.



Cobalt is not altering the chemical structure of the glaze dramatically, even though it is a flux, because such small a concentration is needed to produce strong color. The arrows show the direction of the imaginary line blends of cobalt, from high concentration to low.



Zircopax is used in glazes to make them opaque and strong. It contains many refractory elements and so contributes to the strength of the glaze, as well.



Rutile acts as a flux and causes the glaze to run significantly. More importantly, rutile also produces micro crystallization that looks lovely when mixed with other oxides.

A strategy for triaxial blends recommended by John Britt in his instructional video *Understanding Glazes* (Brit 2003), is to use three variables that act similarly to the three basic components of a glaze. In this particular triaxial blend, cobalt functions as a glass former, rutile as a flux, and zircopax as a stabilizer. There is nothing special that comes from thinking of the 3 variables as the 3 base components except that it is a technique used by several current ceramic artists. To reiterate; triaxial blends may be done with any 3 variables. This idea is more of a rule of thumb than a hard and fast law.

Materials

21 bisque fired tiles	Glaze materials	Sieve
21 disposable cups	Spoon or spatula	Scale
Distilled water	Sharpie	

Method

First, the amount of base glaze needed for 21 glaze test of 100g each was calculated. The number was rounded to 25 to ensure that enough glaze was made to account for accidental spills and evaporation. The amount of oxide added to each test was also calculated at this time, as shown in fig.29.

3124	80g		2000g
EPK	10g	X 25	250g
Flint	10g		250g
Bentonite	2g		50g

Next, 50g of bentonite was poured into 500g of distilled water to hydrate. After 3 days passed, the remaining components were weighed out and added to the distilled water and bentonite, then left them to hydrate for another day. 100g of base glaze was weighed and added to each cup before the additional oxides were added. Each test was then sieved individually. The tests were then left for another day to allow the new components to hydrate. Lastly, test tiles were dipped for 3 seconds each, allowed to dry, dipped again, allowed to dry again, and rubbed to remove pinholes before being fired to cone 5.

	100%	80%	60%	40%	20%
CoO	1g	.8g	.6g	.4g	.2g
Rutile	5g	4g	3g	2g	1g
Zircopax	10g	8g	6g	4g	2g

Fig.29. Oxide amounts added

Results and Discussion

This test produced some of the most beautiful and usable glazes. The most interesting tests were the ones near the middle of the triaxial, where all three components were added.

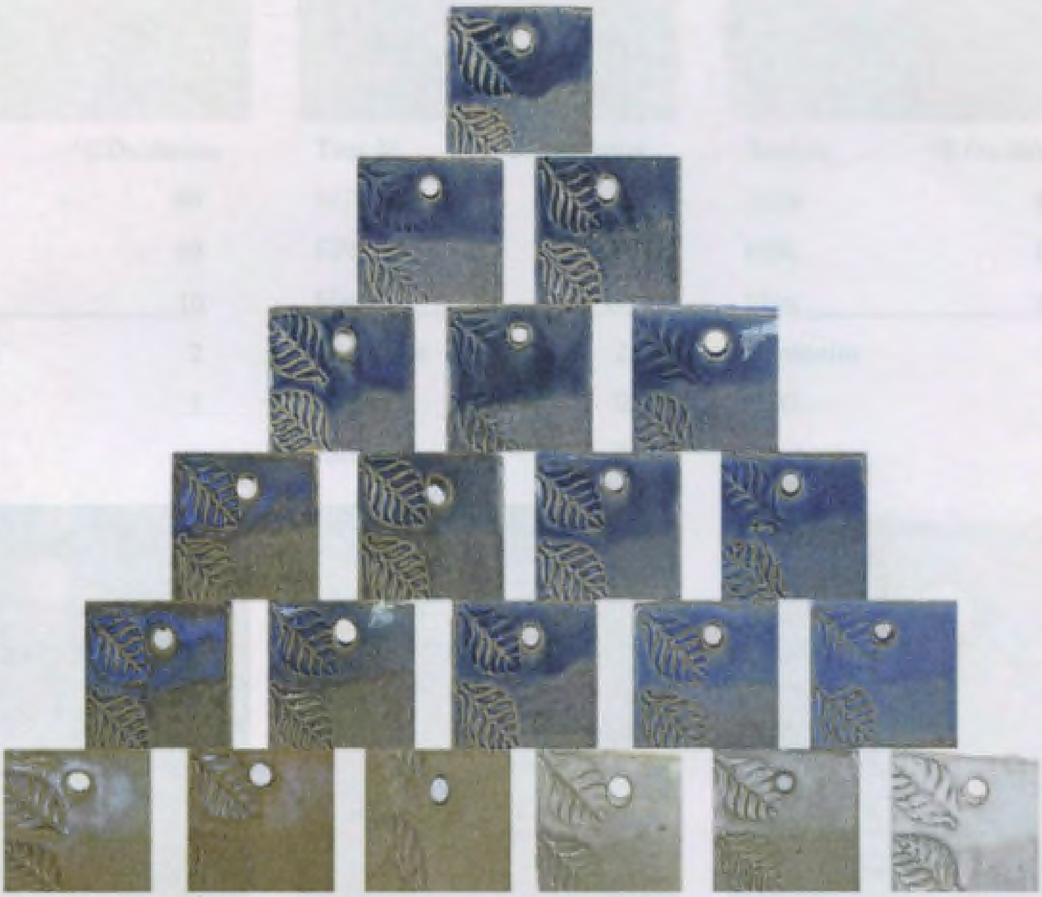


Fig.30. The completed triaxial

Test 1t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	1

Test 2t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.8
Zircopax	2

Test 3t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.6
Zircopax	2

Test 4t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.4
Zircopax	6

Test 5t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.2
Zircopax	8

Test 6t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Zircopax	10

Test 7t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Zircopax	8
Rutile	1

Test 8t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Zircopax	6
Rutile	2

Test 9t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Zircopax	4
Rutile	3

Test 10t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Zircopax	2
Rutile	4

Test 11t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Rutile	5

Test 12t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Rutile	4
CoO	0.2

Test 13t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Rutile	3
CoO	0.4

Test 14t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Rutile	2
CoO	0.6

Test 15t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
Rutile	1
CoO	0.8

Test 16t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.6
Rutile	1
Zircopax	2

Test 17t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.4
Rutile	1
Zircopax	4

Test 18t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.2
Rutile	1
Zircopax	6

Test 19t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.2
Rutile	2
Zircopax	4

Test 20t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.2
Rutile	3
Zircopax	2

Test 21t	^5 Oxidation
3124	80
EPK	10
Flint	10
Bentonite	2
CoO	0.4
Rutile	2
Zircopax	2

Triaxial Body

Introduction

This glaze test followed the same general outline as the previous triaxial. Importantly though, this triaxial used the base Meyers Clear recipe components as its independent variables, as was done in the line test. This means that the outline has to be approached from a slightly different manner. These two tests give a great example of how a single tool can be used to answer many different questions. Keen eyed readers might notice that the ranges for Flint and EPK are the reverse of what you would expect to see. By this I mean that the supposed 20% amount is larger than the 100% amount. This was a mistake, but not a fatal one. It merely means that two axis of the triangle are flipped. Good information may still be gleaned from this test. Like the previous line blend test, these test tiles were made with Zellastone clay, produced by *Highwater Clays*.

Materials

21 bisque fired tiles	Glaze materials	Sieve
21 disposable cups	Spoon or spatula	Scale
Distilled water	Sharpie	

Method

	100%	80%	60%	40%	20%
3124	90	85	80	75	70
Flint	9	9.5	10	10.5	11
EPK	9	9.5	10	10.5	11

Fig. 31. A table showing the range of material amounts used in the test.

Because this test involved variation of the base formula, it was not possible to make a large batch of base glaze to divide into each cup. Instead, each test was treated like an individual glaze. The amounts of materials used to correspond with the triaxial rubric are seen in fig.31. 50g of distilled water were weighed into each cup. 2g of bentonite was added and left to hydrate for 3 days. 50 more grams of distilled water were added to each test before the appropriate components were weighed out and added. The tests were then left for another day to allow the new components to hydrate. Once fully hydrated, sieved, and mixed, the glaze test still appeared too thick so 25 more grams of water were added to each. Lastly, test tiles were dipped for 3 seconds each, allowed to dry, dipped again, allowed to dry again, and finally rubbed to remove pinholes before being fired to ^5.

Results and Discussion

Similar to how the line blend tests behaved, when these tiles were removed from the kiln, none showed any crazing. However, over the course of a week all of the tiles crazed. Tests 8tb and 20tb were the last to craze and showed the fewest cracks. Both these contained more silica than the original formula. Although far from conclusive, I believe that an appropriate next step would be to increase the silica content in Meyers in higher increments. Additionally, further tests may use different clay bodies and firing schedules to ascertain all of the variables contributing to the crazing.

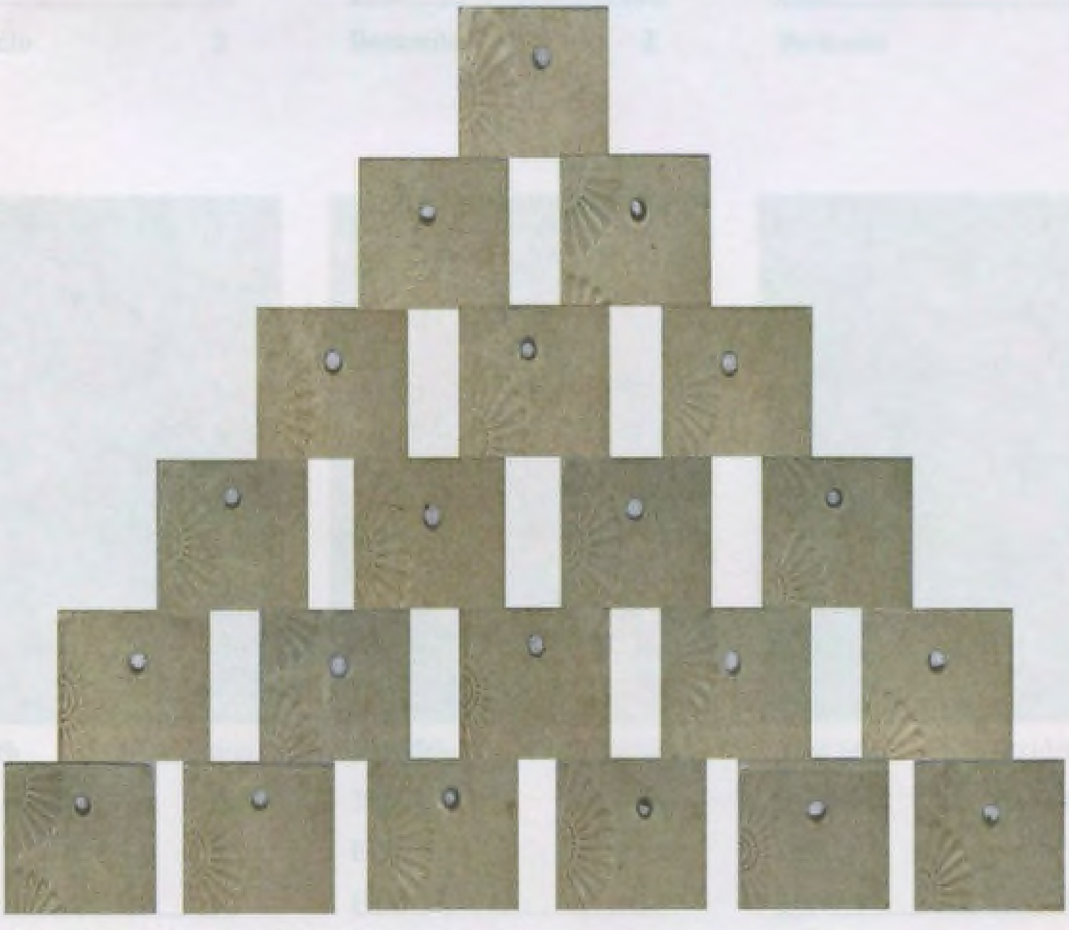


Fig. 32. The completed triaxial

Test 1tb	^5 Oxidation
3124	90
EPK	10
Flint	10
Bentonite	2

Test 2tb	^5 Oxidation
3124	85
EPK	11
Flint	10
Bentonite	2

Test 3tb	^5 Oxidation
3124	80
EPK	10.5
Flint	10
Bentonite	2

Test 4tb	^5 Oxidation
3124	75
EPK	10
Flint	10
Bentonite	2

Test 5tb	^5 Oxidation
3124	70
EPK	9.5
Flint	10
Bentonite	2

Test 6tb	^5 Oxidation
3124	80
EPK	9
Flint	10
Bentonite	2

Test 7tb	^5 Oxidation
3124	80
EPK	11
Flint	9.5
Bentonite	2

Test 8tb	^5 Oxidation
3124	80
EPK	10.5
Flint	10
Bentonite	2

Test 9tb	^5 Oxidation
3124	80
EPK	10
Flint	10.5
Bentonite	2

Test 10tb	^5 Oxidation
3124	80
EPK	9.5
Flint	11
Bentonite	2

Test 11tb	^5 Oxidation
3124	80
EPK	9
Flint	10
Bentonite	2

Test 12tb	^5 Oxidation
3124	70
EPK	9.5
Flint	10
Bentonite	2

Test 13tb	^5 Oxidation
3124	75
EPK	10
Flint	10
Bentonite	2

Test 14tb	^5 Oxidation
3124	80
EPK	10.5
Flint	10
Bentonite	2

Test 15tb	^5Oxidation
3124	85
EPK	11
Flint	10
Bentonite	2

Test 16tb	^5 Oxidation
3124	80
EPK	11
Flint	11
Bentonite	2

Test 17tb	^5 Oxidation
3124	75
EPK	11
Flint	10.5
Bentonite	2

Test 18tb	^5 Oxidation
3124	70
EPK	11
Flint	10
Bentonite	2

Test 19tb	^5 Oxidation
3124	70
EPK	10.5
Flint	10.5
Bentonite	2

Test 20tb	^5 Oxidation
3124	70
EPK	10
Flint	11
Bentonite	2

Test 21tb	^5 Oxidation
3124	75
EPK	10.5
Flint	11
Bentonite	2